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Dynamic Control of the Polarization of Intense Laser Beams Using Optical Wave Mixing in Plasmas

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Lawrence Livermore National Laboratory • National Ignition Facility & Photon Science

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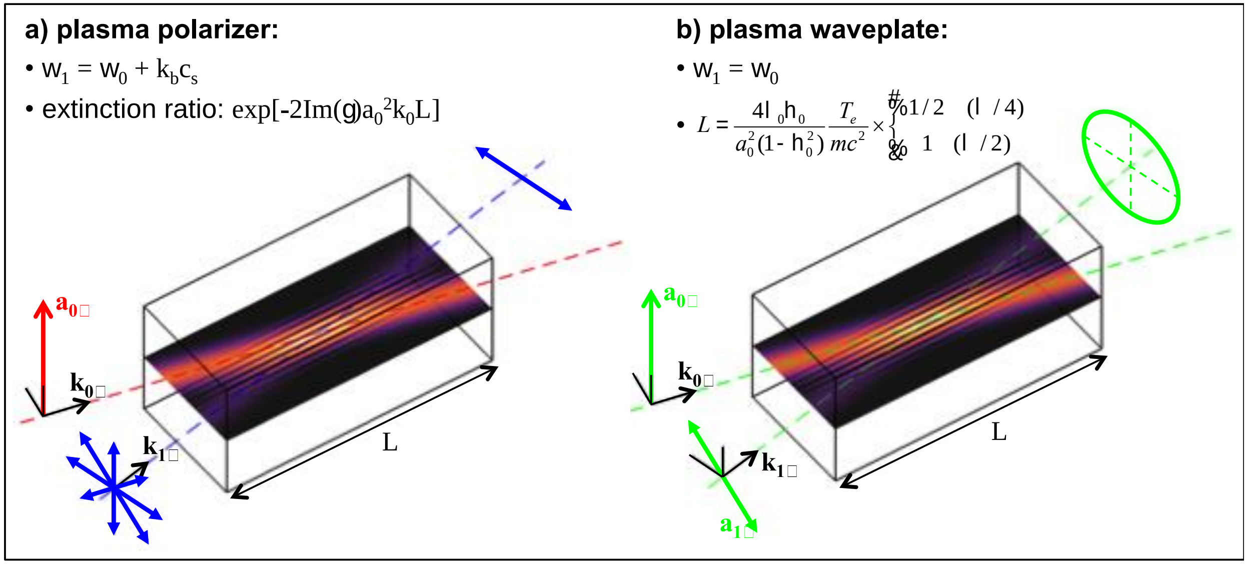
Introduction / Summary

- **The polarization of a "probe" laser beam can be modified by optical mixing with another "pump" laser beam in a plasma**
- **The polarization modification arises from modifications of the beam's amplitude (energy transfer), phase (plasma birefringence) – or both**
- **This could be applied to the design of novel photonics devices with applications such as ultra-fast polarization switching, in-situ polarization smoothing etc.**



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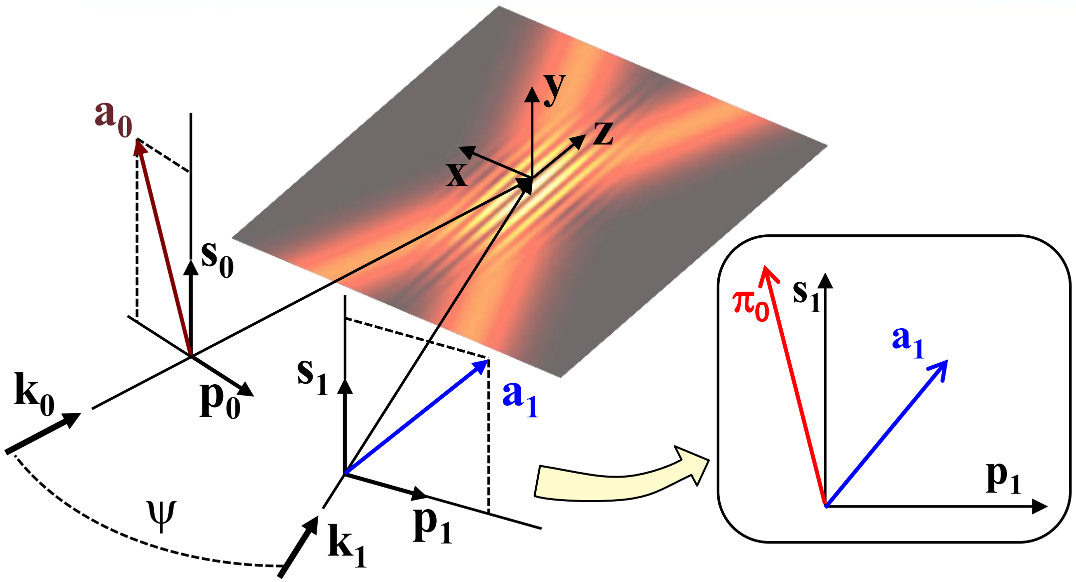
The coupling between two lasers with arbitrary polarizations is described using Jones formalism



Definitions (E-fields' envelopes):

- a_0 = "pump" beam
- a_1 = "probe" beam
- π_0 = projection of a_0 in (p_1, s_1) (probe's plane of polarization)

Jones formalism:

$$|a_0\rangle = \begin{pmatrix} a_{0p} \\ a_{0s} \end{pmatrix}, \quad \langle a_0| = (a_{0p}^* \quad a_{0s}^*), \quad \Rightarrow \langle a_0|a_0\rangle = |\mathbf{a}_0|^2$$

Maxwell equations + linearized Vlasov →
$$\boxed{\begin{aligned} \partial_z|a_1\rangle &= i\gamma^*\langle\pi_0|a_1\rangle|\pi_0\rangle \\ \partial_z|a_0\rangle &= i\gamma\langle\pi_1|a_0\rangle|\pi_1\rangle \end{aligned}}$$

where γ is the plasma response to the beat wave: $\gamma = \frac{1}{2}\frac{\chi_e(1+\chi_i)}{1+\chi_e+\chi_i}\sin(\psi/2)\tan(\psi/2)$

The problem is described by a system of four coupled equations (p&s components for each beam), coupled via the refractive index modulation

The system can be analytically solved in the undepleted pump approximation (probe << pump)

$$\partial_z |a_1\rangle = i\gamma^* \langle \pi_0 | a_1 \rangle |\pi_0\rangle$$
$$\partial_z |a_0\rangle = i\gamma \langle \pi_1 | a_0 \rangle |\pi_1\rangle$$

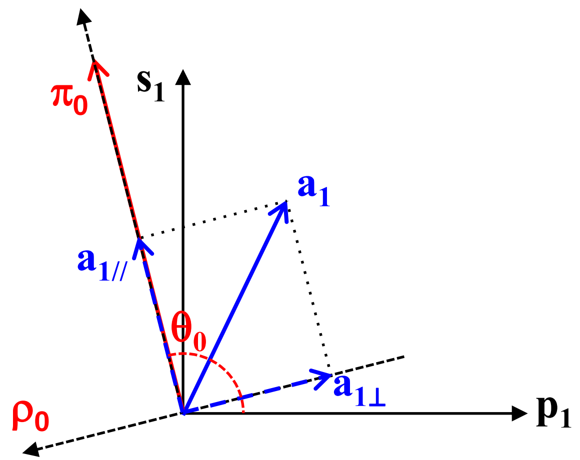
Undepleted pump: $|a_1(z)\rangle$ **,** $|a_0\rangle = \text{constant} \;\; (|\mathbf{a}_1|^2 \ll |\mathbf{a}_0|^2)$

→ **equation for the probe:** $\partial_z |a_1\rangle = M_0 |a_1\rangle$ **where** $M_0 = i\gamma^* |\pi_0\rangle\langle \pi_0|$ **(2x2 matrix)**

Solution for propagation from $z=0$ **to** $z=L$ **: diagonalization + exponentiation of** $\mathbf{M_0}$ →

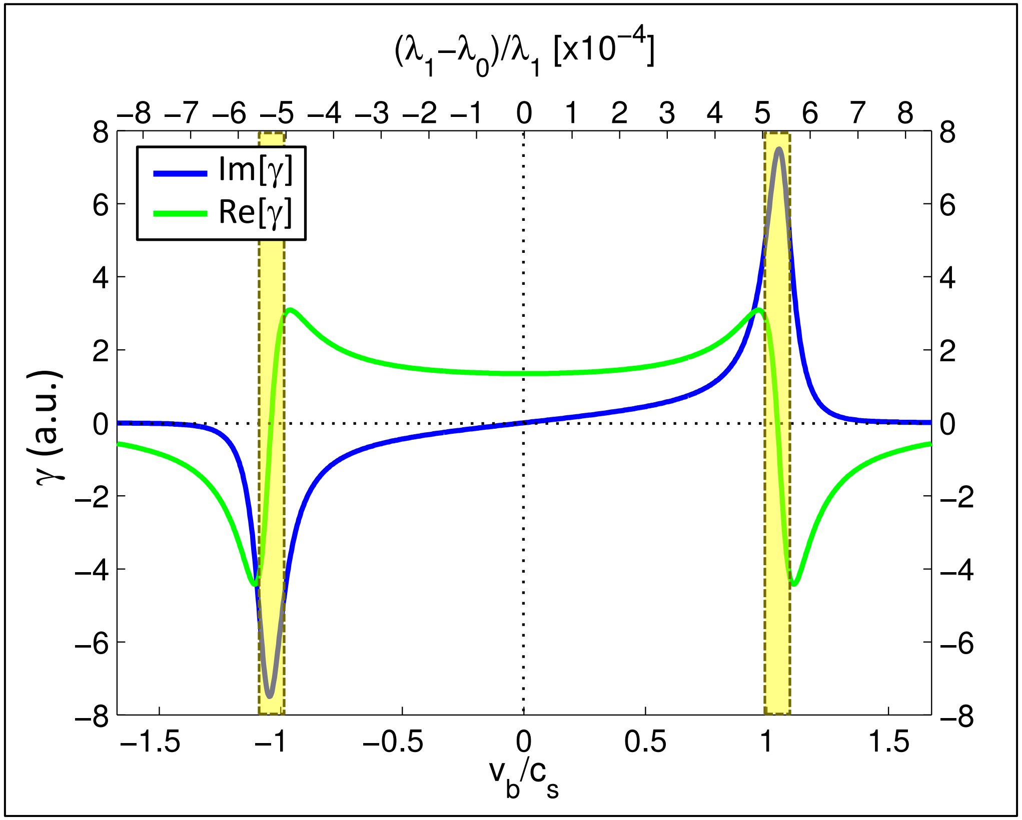
$$\boxed{|a_1(L)\rangle = R(-\theta_0) \begin{pmatrix} \exp[i\gamma^* |\pi_0|^2 k_0 L] & 0 \\ 0 & 1 \end{pmatrix} R(\theta_0) |a_1(0)\rangle}$$

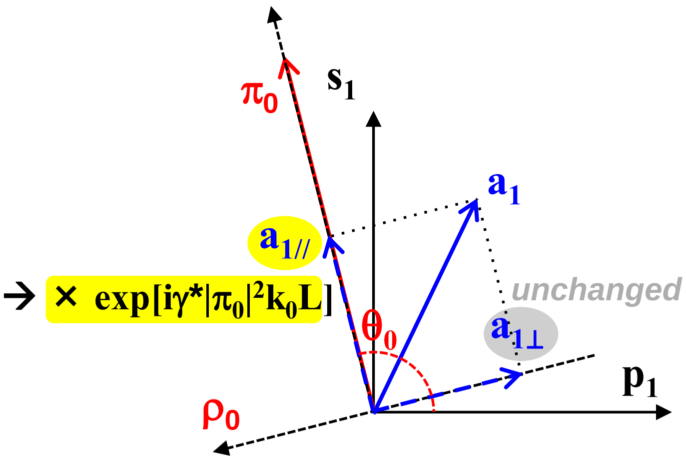
1. $R(\theta_0)$ **: rotation matrix by** θ_0 **(≡angle between** $\mathbf{p_1}$ **and** π_0**): change of basis** $(\mathbf{p_1}, \mathbf{s_1})$ → (π_0, ρ_0)
2. $\mathbf{a}_{1//}$ **is multiplied by** $\exp[i\gamma^* |\pi_0|^2 k_0 L]$ **,** $\mathbf{a}_{1\perp}$ **is unaffected**
3. **rotate back to** $(\mathbf{p_1}, \mathbf{s_1})$



The probe component $\mathbf{a}_{1//}$ parallel to π_0 is modified by the interaction (amplitude and phase, depending on whether γ is complex or real)

The nature of the probe modification (phase vs. amplitude) depends on the wavelength difference between pump and probe





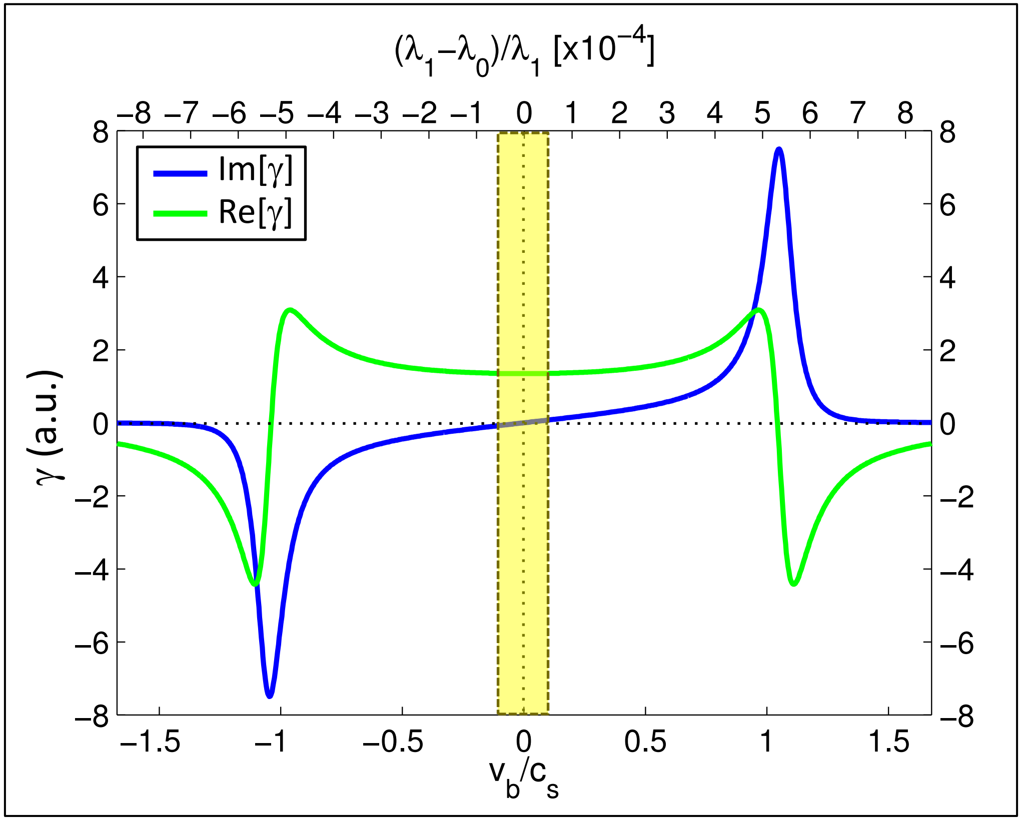
$v_b=(\omega_0-\omega_1)/|\mathbf{k}_0-\mathbf{k}_1|$ = phase velocity of the beat wave

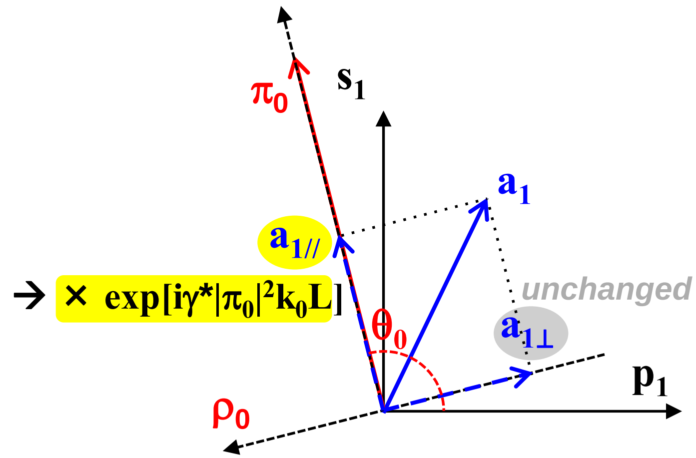
c_s = plasma sound speed

Two notable regimes:

- $v_b \sim \pm c_s$: γ is purely imaginary, ⇒ ***amplitude*** of $a_{1//}$ is modified (pump-probe energy exchange)

The nature of the probe modification (phase vs. amplitude) depends on the wavelength difference between pump and probe





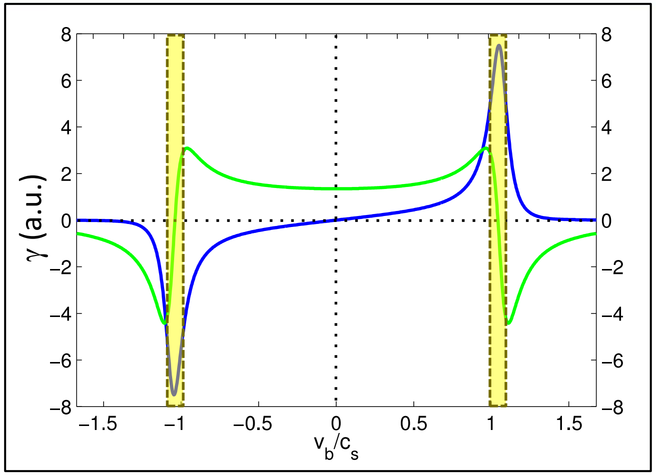
$v_b=(\omega_0-\omega_1)/|\mathbf{k}_0-\mathbf{k}_1|$ = phase velocity of the beat wave

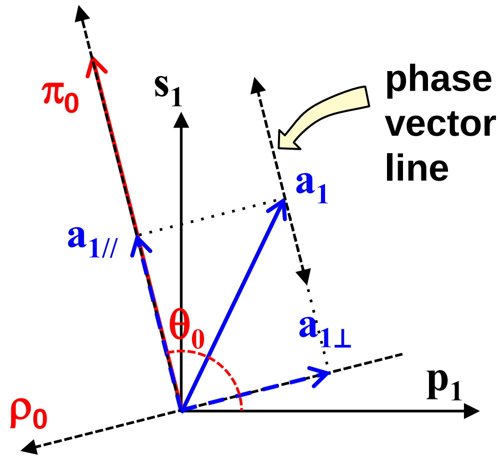
c_s = plasma sound speed

Two notable regimes:

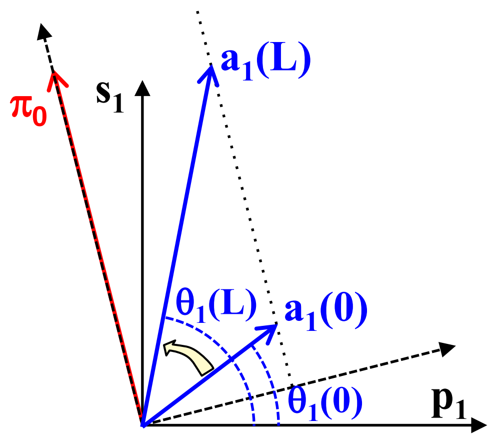
- $v_b \sim \pm c_s$: γ is purely imaginary, ⇒ ***amplitude*** of $a_{1//}$ is modified (pump-probe energy exchange)
- $v_b \sim 0$: γ is purely real, ⇒ ***phase*** of $a_{1//}$ is modified (induced- plasma birefringence)

$\omega_1=\omega_0 \pm |\mathbf{k}_0-\mathbf{k}_1| c_s$ ("non-degenerate wave-mixing"): energy transfer between the pump and $\mathbf{a}_{1//}$





phase of $\mathbf{a}_1$ is constant; field vector evolves along dotted line



After propagation distance L: (assume linearly polarized probe)

- amplitude is modified from $\mathbf{a}_1(0)$ to $\mathbf{a}_1(L)$:

$$a_1(L) = a_1(0)\exp\left[-\mathrm{Im}(\gamma)|\rho_0|^2 k_0 L\right]$$

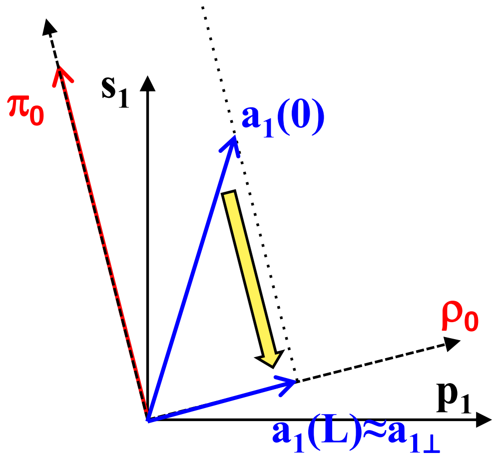
- polarization direction is rotated from $\theta_1(0)$ to $\theta_1(L)$:

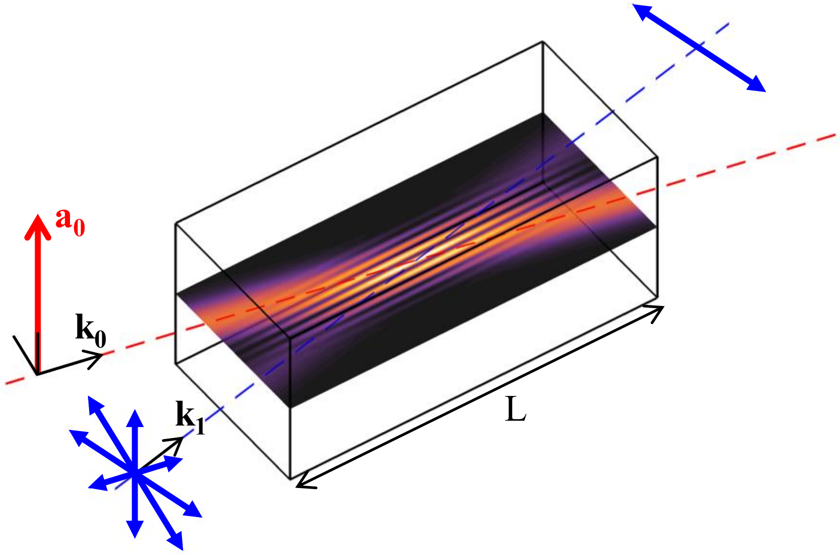
$$\theta_1(L) = \theta_0 - \mathrm{atan}\left[e^{-\mathrm{Im}(\gamma)|\rho_0|^2 k_0 L}\tan\left(\theta_0 - \theta_1(0)\right)\right]$$

Consequence: cross-beam energy transfer between arbitrarily polarized beams can lead to polarization rotation

Application of the non-degenerate case ($v_b \sim \pm c_s$): plasma polarizer

- Pick v_b=-c_s (energy transfer probe → pump): $a_{1//}$ component vanishes
- ⇔ polarizer along ρ_0 with extinction ratio $\mu = \exp[-2\mathrm{Im}(\gamma)|\pi_0|^2 k_0 L]$
- most efficient configuration: s-polarized pump ($\pi_0 = a_0$)



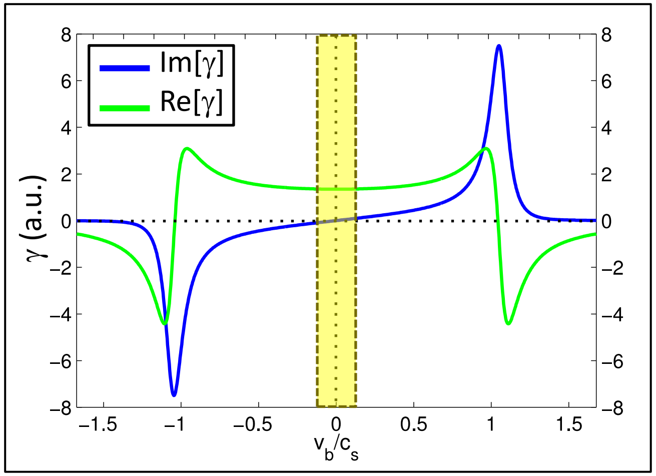


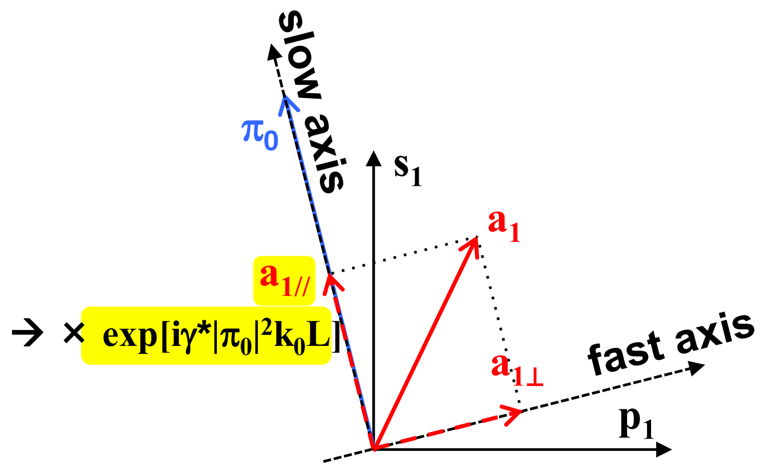
Example:

- typical ICF/HED laser/plasma conditions: Te=3 keV, Ti=1 keV, λ_0=351 nm, n_e=0.1n_c
- pump intensity $I_0 = 10^{15}$ W/cm^2, propagation length = 300 μm
- → <u>extinction ratio = 10^{-5}</u>

Non-degenerate wave-mixing can be used to design very efficient plasma polarizers

$\omega_0=\omega_1$ ("degenerate wave-mixing"): no energy transfer but phase retardation of $a_{1//}$ w.r.t. $a_{1\perp}$: plasma birefringence





If $\omega_0=\omega_1$: $\mathrm{Re}[\gamma]>0$, $\Rightarrow$ $a_{1//}$ is retarded with respect to $a_{1\perp}$

→ The pump's electric field breaks the optical isotropy of the plasma, similar to anisotropic binding forces between atoms in a crystal

Fast and slow refraction indices:

$$\eta_{fast} = \eta_0 = \sqrt{1 - \frac{n_e}{n_c}}$$

$$\eta_{slow} = \eta_0\left[1 + \gamma\cos(\psi/2)|\pi_0|^2\right]$$

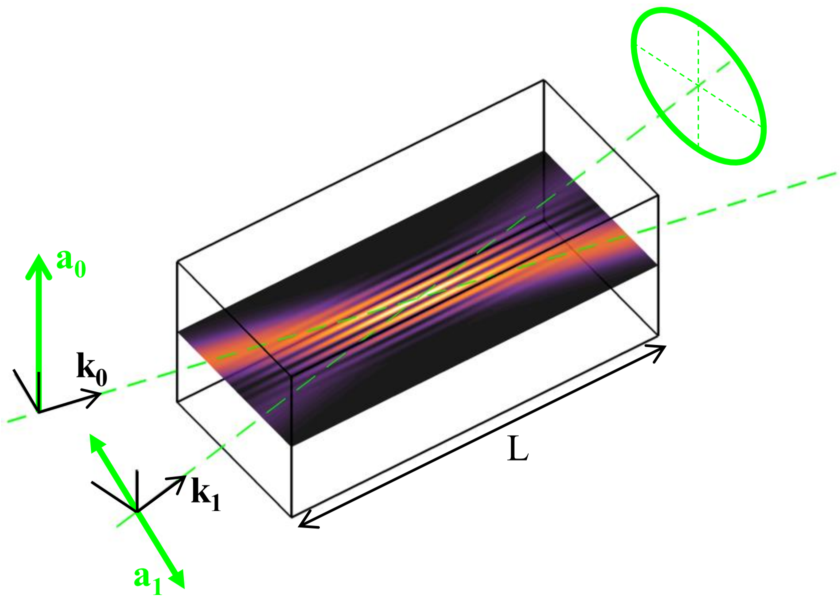
A "pump+plasma" system can act like a birefringent medium for a probe laser beam

Application of the degenerate case ($\omega_0=\omega_1$): plasma waveplate

Interaction length required for a quarter ($\lambda/4$) or half ($\lambda/2$) plasma waveplate:

$$L=\frac{\lambda_0}{2|\pi_0|^2\eta_0\gamma\cos(\psi/2)}\times\begin{cases}1/2 & (\lambda/4)\\ 1 & (\lambda/2)\end{cases}$$

Note: if $ZT_e/T_i \gg 1$, then $L \propto T_e/(I_{pump} \times n_e)$



Example:

- **T_e=3 keV, T_i=1 keV, λ_0=351 nm, n_e=0.1n_c , $I_0=10^{15}$ W/cm^2**
- **s-polarized pump, probe linearly polarized at 45° from the pump**
- **→ $L_{\lambda/4}$~500 µm**

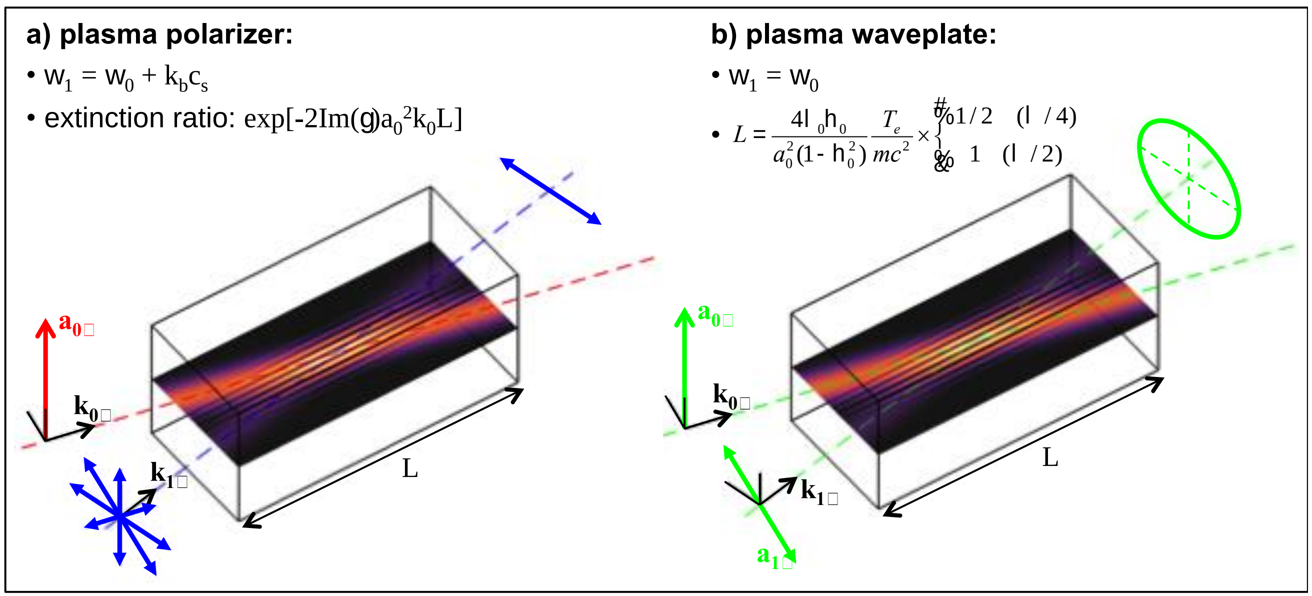
- Polarizers and wave-plates constitute the basic building blocks for other active or passive optics devices (rotators, Pockel cells etc.)
- In a plasma: response time can be ultra-fast (sub-ps)

Conclusion / Summary

- **non-degenerate wave-mixing with $\omega_1=\omega_0\pm|\mathbf{k_0}-\mathbf{k_1}|c_s$: amplitude modification of $\mathbf{a}_{1//}$ (probe component parallel to the pump); <u>application: plasma polarizer</u>**

- **degenerate wave-mixing ($\omega_1=\omega_0$): the phase of $\mathbf{a}_{1//}$ is retarded w.r.t. $\mathbf{a}_{1\perp}$ (plasma birefringence); <u>application: plasma waveplate</u>**

- **such plasma devices are resistant to high laser fluxes (unlike crystals) and can have ultra-fast response times (sub-ps)**



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